

The Bar-enhanced Star-formation Activities in Spiral Galaxies

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Abstract. We use the ratio $L_{\text{FIR}}/L_{\text{B}}$ and the IRAS color index S_{25}/S_{12} (both widely used as indices of relative star formation rates in galaxies) to analyse subsets (containing no known AGNs or merging/interacting galaxies) of: (a) the IRAS Bright Galaxy Sample, (b) galaxies from the optically complete RSA sample which have IRAS detections in all four bands, and (c) a volume-limited IR-unselected sample. We confirm that IR-bright barred (SB) galaxies do, on average, have very significantly higher values of the FIR-optical and S_{25}/S_{12} ratios (and presumably, higher relative star formation rates, SFR) than that do unbarred ones; the effect is most obvious in the IR colors. We also confirm that these differences are confined to early-type (S0/a - Sbc) spirals and are not evident among late-type systems (Sc - Sdm). *Unlike others, we see no enhancement of the SFR in weakly-barred (SAB) galaxies.* We further confirm that the effect of bars on the SFR is associated with the relative IR luminosity and show that it is detectable only in galaxies with $L_{\text{FIR}}/L_{\text{B}} \gtrsim 1/3$, suggesting that as soon as they have any effect, bars translate their host galaxies into this relatively IR-luminous group. Conversely, for galaxies with $L_{\text{FIR}}/L_{\text{B}}$ below ~ 0.1 this luminosity ratio is *lower* among barred than unbarred systems, again confirming and quantifying an earlier result. Although there is no simple physical relation between HI content and star formation, a strong correlation of HI content with the presence of bars has been found for early-type spirals with $L_{\text{FIR}}/L_{\text{B}} \gtrsim 1/3$. This suggests that the availability of fuel is the factor determining just which galaxies undergo bar-induced starbursts.

Key words: Galaxies: starburst – Galaxies: spiral – Galaxies: statistics – Stars: formation of

1. Introduction

For well over a decade, models of the dynamics of the interstellar medium (ISM) in spiral galaxies (e.g. Roberts, Huntley & van Albada, (1979); Schwarz (1984); Combes & Gerin (1985); Byrd et al (1986); Noguchi (1986, 1988), *inter alia*, see also the review by Athanassoula 1992) have suggested that the presence of a central bar generates an inflow of gaseous interstellar medium (ISM) which accumulates at the inner Lindblad resonance (ILR), if it exists, or else near the nucleus. Such inflows are obviously potential raw material for a burst of star formation in the center of the galaxy, and it has been known for three decades that bars are indeed strongly associated with the presence of “hot-spots” and other peculiar central structures in spirals (e.g. Sérsic& Pastoriza (1965 and 1967).

Nevertheless, there is still an active debate on the nature and degree of the dependence of star formation activity on barred morphology.

Observations at radio wavelengths by Hummel (1981) suggested that the radio luminosity of central sources in barred spirals (SB+SAB types) are on average a factor 2 more powerful than those in ordinary spirals (SA type). The extension of this work by Puxley et al. (1988) showed a strong correlation between the presence of a compact radio nucleus and barred morphology (SB+SAB). In the mid and far-IR the IRAS catalogue has permitted a wide range of studies. de Jong et al. (1984) found that IRAS had a higher detection rate for barred than for unbarred spirals and that the barred systems tended to have hotter FIR colors. Hawarden et al. (1986a,b) found a strong dependence of IRAS *mid*-IR colors on barredness. Devreux (1987) also found this effect, and noted that the presence of bars was strongly correlated with the concentration near the nucleus ($\lesssim 5''$) of a large fraction of the total emission at $10\mu\text{m}$ wavelength. A similar conclusion to that of Hawarden et al. was reached by Dressel (1988):

the presence of a bar appeared clearly to affect the SFR in S0, Sa and Sb galaxies but (in agreement with Devereux) not in late types. Enhancement of star formation rates inferred from optical ($H\alpha$) data was also seen in barred galaxies by Arsenault (1989).

On the other hand, $10\mu\text{m}$ observations of a nearby, relatively faint galaxy sample (Devereux et al. 1987) show no evidence for enhanced near-nuclear emission in barred systems. Eskridge & Pogge (1991) argued that the presence or absence of bars does not affect the SFR in S0 galaxies, while Isobe & Feigelson (1992) found that barred galaxies in a volume-limited (low-luminosity) sample had lower overall FIR luminosities than unbarred galaxies. A search in the near-IR for bars in an IR-bright sample of 16 non-Seyfert, non-interacting galaxies by Pompea & Rieke (1990) appeared to show that IR bars are not a necessary prerequisite for strong infrared activity in such isolated, non-AGN galaxies.

Perhaps these apparently discrepant studies can be understood if we recall that some groups worked on optically-selected samples of normal spiral galaxies while others used samples extracted from the IRAS catalogue, some deliberately selected to be IR-Bright. Statistically, the sources in the IRAS catalogue, especially IR-Bright galaxies, differ markedly from normal spirals (Mazzarella et al 1991), so differences in current star formation levels and their governing factors are likewise to be expected. Such differences were foreshadowed by Devereux et al. (1987) who found in studying the IR characteristics of normal nearby galaxies that dependence of SFR on bar morphology is related to IR luminosities, being absent in low-luminosity systems.

To help understand such effects we have constructed a new IR-luminous sample, the details of which are presented in Section 2. The results of our analysis of this sample and similar analyses of two other samples taken, or updated, from previous studies are presented in Section 3, with a comparison of their properties. The combined analyses of these samples suggests a simple unified picture of the influence of barred morphology on star formation in, and on the IR properties of, spiral galaxies.

2. A New Sample, and Statistical methods

2.1. The IR-Bright Galaxy Sample

To explore the effects of sample properties on the apparent influence of barred morphology on the far-infrared properties for spiral galaxies, we have constructed a sample which is deliberately intended to be IR-bright. It is derived from IRAS Bright Galaxies Sample (Soifer et al. 1989), the main selection criterion for which is a $60\mu\text{m}$ flux density ≥ 5.4 Jy, and which includes a variety of classes of galaxies, including AGN, mergers and strongly interacting galaxies. All of these tend to contain warm dust, whether or not from star formation (Miley et al 1985; Lonsdale et al

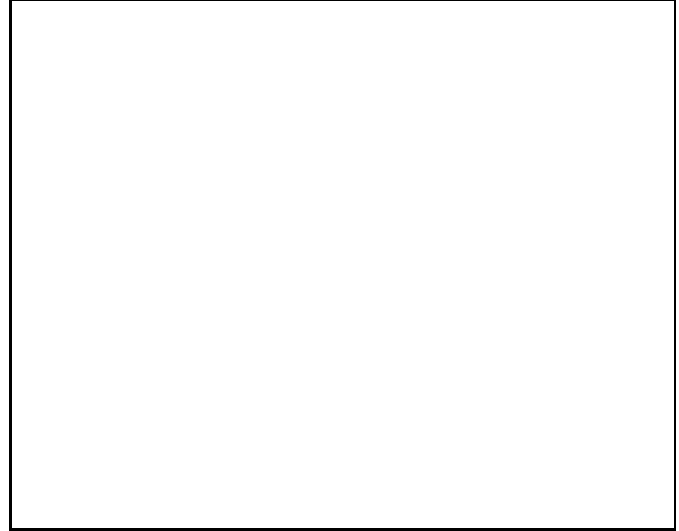


Fig. 1. Cumulative distributions of $L_{\text{FIR}}/L_{\text{B}}$ for galaxies in IRAS Bright Galaxies Sample with some sources removed, see text. The distributions for types SA, SAB, and SB are indicated by open circles, crosses, and filled circles, respectively.

1984; Sanders et al 1988; Mazzarella et al 1991; Surac et al 1993; and references therein) and independent of the presence of barred morphology. In order to isolate the effects of just this morphology on star formation, we define a subsample by excluding all active nuclei (Seyferts and LINERs) listed by Véron-Cetty & Véron (1993), and all mergers and strongly interacting galaxies listed by Lonsdale et al. (1984). We also require that each object be assigned a definite Hubble type S in the Reference Catalog, which will also exclude some morphologically peculiar galaxies. We refer to the resulting subsample as the IR-Bright Galaxy Sample (the IRBG sample).

Fig 1 shows a cumulative distribution of $\log L_{\text{FIR}}/L_{\text{B}}$ for this sample. It is immediately apparent that the SB systems differ from the SAs. However, rather unexpectedly, the SAB galaxies are indistinguishable from the unbarred systems; in the next section we provide statistical confirmation, while later we return to this issue with a test and sample in which barred galaxies show an even stronger difference from the SA systems; once more no difference between SAB and SA systems is discernable.

In sharp contrast, Fig 1 of Hawarden et al. (1986b) shows a clear difference between their SAB and SA samples. The former contains 12 galaxies with IRAS $25\mu\text{m}$ fluxes 2.2 or more times stronger than the $12\mu\text{m}$ flux, and above and below this threshold. From a $2 \times 2 \chi^2$ test with Yates' corrections the probability that the two groups are the same P_{null} is < 0.005 . We note that the sample of Pompea & Rieke (1990) (discussed below) also suggests that SAB systems differ from SAs in having higher SFRs. These contradictions will be explored elsewhere; in this

analysis we simply omit all SAB galaxies, except in the discussion of the work by Pompea & Rieke.

Details of the 123 objects remaining in the present sample (the BG sample), ranging from S0/a to Sdm in type, are listed in Table 1 as follows: column (1), the NGC, UGC, and IC number; column (2), the morphological type from RC3 (de Vaucouleurs et al 1991 , hereafter RC3); column (3), the recessional velocities corrected to the Galactic Center from RC3; column (4), distance in Mpc. Following Soifer et al (1989), where a “primary distance/Fisher-Tully distance” was available this is given in preference to the radial velocity distance. Primary distances are taken from Sandage & Tammann (1981), while Fisher-Tully distances are taken from Aaronson et al (1982) or Aaronson and Mould (1983), and adjusted to a Virgo distance of 17.6 Mpc (corresponding to a Hubble constant of $75 \text{ km s}^{-1} \text{ Mpc}^{-1}$); column (5), the total blue magnitude from RC3; column (6), logarithm (base 10) of the FIR luminosity in L_{\odot} from 40 to $120 \mu\text{m}$, which is given by (Lonsdale et al 1985)

$$L_{\text{FIR}} = 3.75 \cdot 10^5 \cdot D^2 (2.58 S_{60} + S_{100})$$

where S_{60} and S_{100} are the flux densities at $60 \mu\text{m}$ and $100 \mu\text{m}$ in Jy, from Soifer et al (1989), D is the distance in Mpc; column (7), logarithm (base 10) of the blue luminosity in L_{\odot} , computed from B_T^0 using the formula (Pogge & Eskridge 1993)

$$\log L_B = 12.208 - 0.4B_T^0 + \log(1+z) + 2\log D$$

where z is the redshift of the galaxy.

2.2. Statistics and Statistical Methods

Our sample is not large enough to analyse for the effects of barredness in each morphological subtype. Instead, following Combes & Elmegreen (1993), we have separated our sample into just two groups: early types (S0/a through Sbc) and late types (Sc through Sdm). We treat the S0/a galaxies as spirals because the distribution of their relative FIR emission differs from that of lenticulars (Eskridge & Pogge 1991), and the distribution of their HI content closely resembles that of the Sa systems (Wardle & Knapp 1986).

The far-IR luminosity L_{FIR} measures not only the star-forming rate, SFR, but also the *size* of a galaxy. We must therefore normalize the total luminosities, e.g. to the actual projected area, or to the optical luminosity of the galaxy. Mazzarella et al. (1991) showed that both these normalizations give similar results. Since the quantity L_{FIR}/L_B is now widely used as an indicator of relative star formation rate in analysing the infrared properties of galaxies (e.g. Keel 1993; Combes et al 1994; Helou & Bica 1993), we will use this quantity to discuss the bar-enhancement of star formation in this paper.

Hawarden et al. (1986a) discuss the use of the mid-IR *color* S_{25}/S_{12} , as a sensitive indicator of elevated star formation activity. Hawarden et al (1986b) employed this parameter in their analysis; we will also do so, in parallel with L_{FIR}/L_B .

We have adopted two main tests for the samples examined here. To verify the similarity or difference of samples we compare cumulative distributions of the property being examined (generally L_{FIR}/L_B or S_{25}/S_{12}) by means of the two-sample Kolmogorov-Smirnov test (KS). We estimate the significance of differences in the mean properties of samples by the student’s t test. Occasionally, where obvious (or predefined) dividing lines exist in two properties, the difference between two samples is illustrated by a simple $2 \times 2 \chi^2$ test with Yates’ corrections for small numbers.

The basic statistical results presented in this paper are summarized in Table 2. The following section discusses the individual results in more detail.

3. Comparison of Samples

3.1. Analysis of the BG sample

Fig 2 shows cumulative distributions of $\log L_{\text{FIR}}/L_B$ for barred and unbarred galaxies in the BG sample, the early types in Fig 2a and the late types in Fig. 2b.

In the latter figure the late-type SBs have mean $\log L_{\text{FIR}}/L_B = -0.38$, which is not significantly different from that of the SAs ($p_t \sim 0.65$). Similarly, the KS test indicates a probability $P_{\text{null}} = 0.71$ that the 23 barred and 33 unbarred late-type galaxies are drawn from the same parent population with respect to the optical-FIR luminosity ratio.

However among the early-type galaxies the mean of L_{FIR}/L_B for SBs is about 1.8 times higher than for SAs, and the difference is significant: $p_t \sim 0.005$. The two sample KS test now gives $P_{\text{null}} \sim 0.03$, suggesting a real bar-enhancement of the SFR for the early-type systems. We also note in Fig 2a that this difference only becomes apparent for $L_{\text{FIR}}/L_B \gtrsim 1/3$

Elmegreen & Elmegreen (1985, 1989) and Combes & Elmegreen (1993) have discussed the different properties of bars in early- and late-type spirals. Those in early-type systems are relatively long and strong, with quite flat intensity distributions, while those in late-type galaxies are rather short and weak and their intensities vary exponentially along the bar. The weaker bars in the later types are likely to be less effective at driving the inward flow of gas, and consequently to have lower levels of induced star formation. Furthermore, in late-type galaxies the nucleus contributes on average less than 10% to the FIR luminosity (Devereux et al. 1987), so a change in that fraction, even by quite a large factor, will have a small effect on the overall properties of the galaxy. Conversely, the strong bars common in early-type galaxies may be expected to

Table 2. Summary Statistics

parameter		BG		HP		IF		combined	
name	option	early	late	early	late	early	late	early	late
$\overline{\log L_{\text{FIR}}/L_{\text{B}}}$	barred	-0.0455(33*)	-0.384(23)	-0.870(35)	-0.888(19)	-1.356(8)	-1.062(13)	-0.569(68)	-0.724(46)
	unbarred	-0.298(36)	-0.420(33)	-0.830(38)	-0.860(28)	-1.105(10)	-1.037(15)	-0.622(65)	-0.686(61)
	KS^{\dagger}	0.03	0.71	0.76	0.37	0.33	0.94	0.20	0.98
	t^{\ddagger}	0.005	0.65	0.72	0.82	0.42	0.85	0.62	0.65
$\overline{\log L_{\text{FIR}}/L_{\text{B}}}$ ($L_{\text{FIR}}/L_{\text{B}} > 1/3$) §	barred	0.0362(29)	-0.251(16)	-0.080(7)	-0.231(2)	¶	¶	0.015(34)	-0.251(16)
	unbarred	-0.153(27)	-0.196(18)	-0.312(9)	-0.360(6)			-0.179(31)	-0.197(20)
	KS^{\dagger}	0.05	0.70	0.23	0.68			0.03	0.70
	t^{\ddagger}	0.02	0.45	0.10	0.27			0.007	0.45
$\overline{\log L_{\text{FIR}}/L_{\text{B}}}$ ($L_{\text{FIR}}/L_{\text{B}} < 1/3$) §	barred	-0.638(4)	-0.689(7)	-1.067(28)	-0.965(17)	-1.716(6)	-1.062(13)	-1.153(34)	-0.977(30)
	unbarred	-0.734(9)	-0.688(15)	-0.990(29)	-0.990(22)	-1.196(9)	-1.108(14)	-1.025(34)	-0.924(41)
	KS^{\dagger}	0.92	0.99	0.70	0.46	0.08	0.80	0.47	0.85
	t^{\ddagger}	0.36	0.99	0.40	0.84	0.03	0.67	0.188	0.457
$\overline{S_{25\mu\text{m}}/S_{12\mu\text{m}}}$	barred	2.334(59)		1.583(48)		¶		1.994(92)	
	unbarred	1.749(73)		1.225(65)				1.564(107)	
	KS^{\dagger}	0.00348		0.030				0.009	
	t^{\ddagger}	0.0015		0.020				0.003	
$\overline{S_{25\mu\text{m}}/S_{12\mu\text{m}}}$ ($L_{\text{FIR}}/L_{\text{B}} < 1/3$) §	barred	1.570(11)		1.351(39)		¶		1.273(41)	
	unbarred	1.237(24)		1.160(50)				1.190(53)	
	KS^{\dagger}	0.04		0.39				0.63	
	t^{\ddagger}	0.056		0.17				0.47	

* The numbers in parentheses are number of sources for each subsample

\dagger The probability that the barred and unbarred systems are from the same parent population, derived from the KS test.

\ddagger The probability that the barred and unbarred systems are from the same parent population, derived from the t test.

\S The statistics are performed for sources with $L_{\text{FIR}}/L_{\text{B}} >$ or $< 1/3$.

¶ The sample is too small, or no data available for statistics.

be much more efficient movers of gas, and, being longer, to have a larger collection range from which to supply the inflow; such features may reasonably be expected to generate powerful enhancements in SFRs. Moreover, the nuclear contribution to the FIR luminosity in early types is about 30% (Devereux et al. 1987) so such enhancements will have greater impact on the overall properties of the system.

The apparent confinement of the SRF-enhancing effects of bars to early type systems is therefore easily understood, at least qualitatively.

3.2. Comparison with the results obtained by Hawarden et al. (1986)

Hawarden et al. (1986b) and Puxley et al. (1988) examined samples comprising galaxies from the optically-complete magnitude-limited Revised Shapley Ames catalogue (RSA: Sandage & Tammann 1981) with detections in all four bands in the IRAS Point Source Catalog (1985). They found that galaxies with IRAS flux ra-

tio $S_{25\mu\text{m}}/S_{12\mu\text{m}} > 2.2$ are almost of types SB or SAB. We have produced an updated sample by selecting from the RSA those galaxies with morphological types between S0/a and Sdm in the RC3 (de Vaucouleurs et al. 1993) which have detections in all four IRAS bands in the IRAS PSC (Version 2). After excluding all known AGN (Seyfert 1 and 2 and, unlike Hawarden et al., also all LINERs) in the catalogue by Véron-Cetty & Véron (1993) and, for uniformity (Section 2) all SAB systems, as well as the morphologically peculiar, post-merger system NGC 2146 (RC3: of SBabP) we are left with a list of 120 objects (hereafter the HP sample).

Fig 3a and Fig 3b illustrate the distributions of $\log L_{\text{FIR}}/L_{\text{B}}$ for early- and late-type galaxies, respectively, in this sample. The lack of any major difference between SB and SA systems, whether early or late type, is obvious and confirmed by the KS test : the probability that the barred and unbarred sets are from the same parent population is 0.76 (early-type) and 0.37 (late-type), respectively. Consistent with this result, the mean $\log L_{\text{FIR}}/L_{\text{B}}$ for early- and late-type barred/unbarred galaxies (-0.870/-

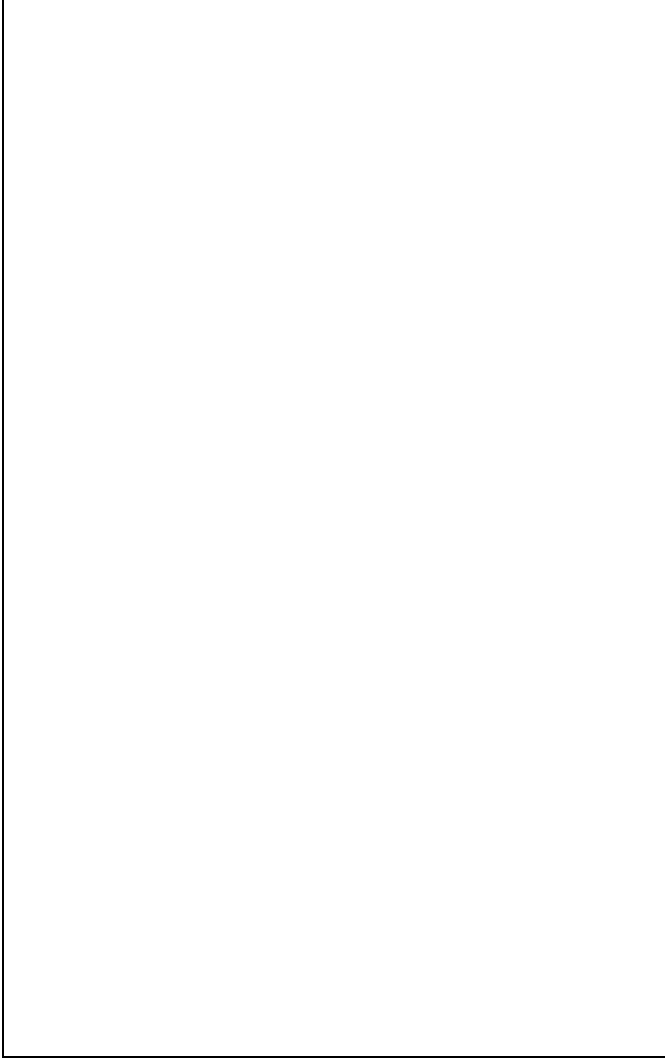


Fig. 2. Cumulative distributions of $L_{\text{FIR}}/L_{\text{B}}$ for barred (filled circles) and unbarred (open circles) galaxies in BG sample. The distributions of early- and late-type galaxies are shown in (a) and (b), respectively.

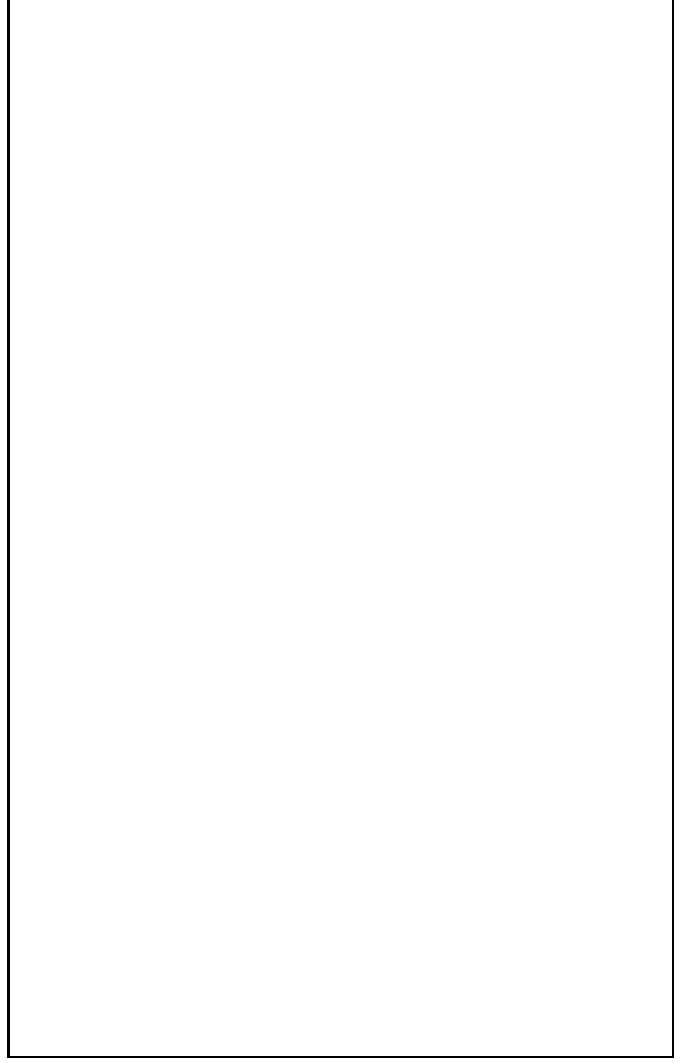


Fig. 3. Cumulative distributions of $L_{\text{FIR}}/L_{\text{B}}$ for barred (filled circles) and unbarred (open circles) galaxies in HP sample. The distributions of early- and late-type galaxies are shown in (a) and (b), respectively.

0.830 and -0.888/-0.860 respectively) are not significantly different either ($p_t \sim 0.72, 0.82$). All the above statistical results indicate that the presence of bars, whether for early- or late-type galaxies, does not measurably enhance the SFRs in this hybrid optical/IR selected sample.

However, the mean $L_{\text{FIR}}/L_{\text{B}}$ for the galaxies in Fig. 3 is well below that of the BG sample. We remarked in Section 3.1 that the apparent enhancement of $L_{\text{FIR}}/L_{\text{B}}$ in SBs relative to SAs in the BG sample is only apparent when $L_{\text{FIR}}/L_{\text{B}} > 1/3$. If we divide the distribution in Fig 3a into two parts at this value of $L_{\text{FIR}}/L_{\text{B}}$, we find that for systems with $L_{\text{FIR}}/L_{\text{B}} < 1/3$, the mean value of the ratio for 28 barred galaxies is indistinguishable from that for the 29 unbarred systems (0.086/0.102) ($p_t \sim 0.40$), but among galaxies with $L_{\text{FIR}}/L_{\text{B}} > 1/3$ the mean for the

seven SB objects is 1.7 times higher than that for the 10 SAs, a marginally significant difference ($p_t \sim 0.1$).

The initial apparently null result does not directly contradict the results of Hawarden et al. (1986b), as their study concentrated on IR rather than IR/Optical colors and luminosities. We therefore show in Fig 4 the distribution of the ratio S_{25}/S_{12} – used by Hawarden et al. (1986b) – for the HP sample. Fig 4a illustrates the distribution for the whole HP sample. Barred and unbarred galaxies are now distributed very differently: a 2×2 χ^2 test with division of the samples about $S_{25}/S_{12} = 2.2$ indicates that the probability that the barred and unbarred galaxies are drawn from the same population is $\ll 0.001$. The difference is evidently real, in agreement with the results of Hawarden et al (1986b); the mean S_{25}/S_{12} for barred galaxies is significantly higher than that for

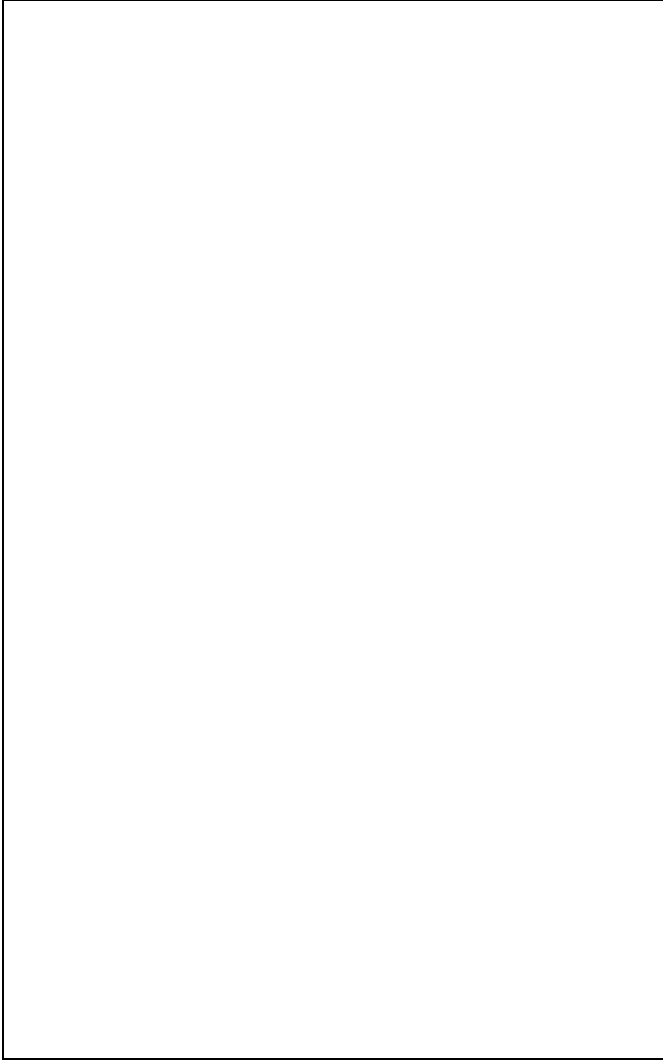


Fig. 4. Cumulative distributions of the $25\mu\text{m}$ to $12\mu\text{m}$ fluxes ratio for barred (filled circles) and unbarred (open circles) galaxies in HP sample. (a) for whole HP sample, (b) for galaxies with $L_{\text{FIR}}/L_{\text{B}} < 1/3$ in HP sample.

unbarred sources ($1.583/1.225$, $p_t \sim 0.020$), in agreement with the KS test, which gives $P_{\text{null}} \sim 0.03$.

Fig 4b shows the distribution of S_{25}/S_{12} for sources in the HP sample with $L_{\text{FIR}}/L_{\text{B}} < 1/3$. Now the mean S_{25}/S_{12} for SBs is not significant different from that for SA systems ($1.351/1.160$, $p_t \sim 0.17$, or $P_{\text{null}} \sim 0.39$ from the KS test). Again, this time from analysis of the S_{25}/S_{12} colors, the effects of barred morphology are seen only when $L_{\text{FIR}}/L_{\text{B}} > 1/3$.

3.3. Comparison to results obtained by Isobe & Feigelson (1992)

Isobe & Feigelson (1992) have recently carried out survival analysis on a volume-limited sample ($v \leq 1400 \text{ km s}^{-1}$) selected from the Zwicky Catalog, and concluded

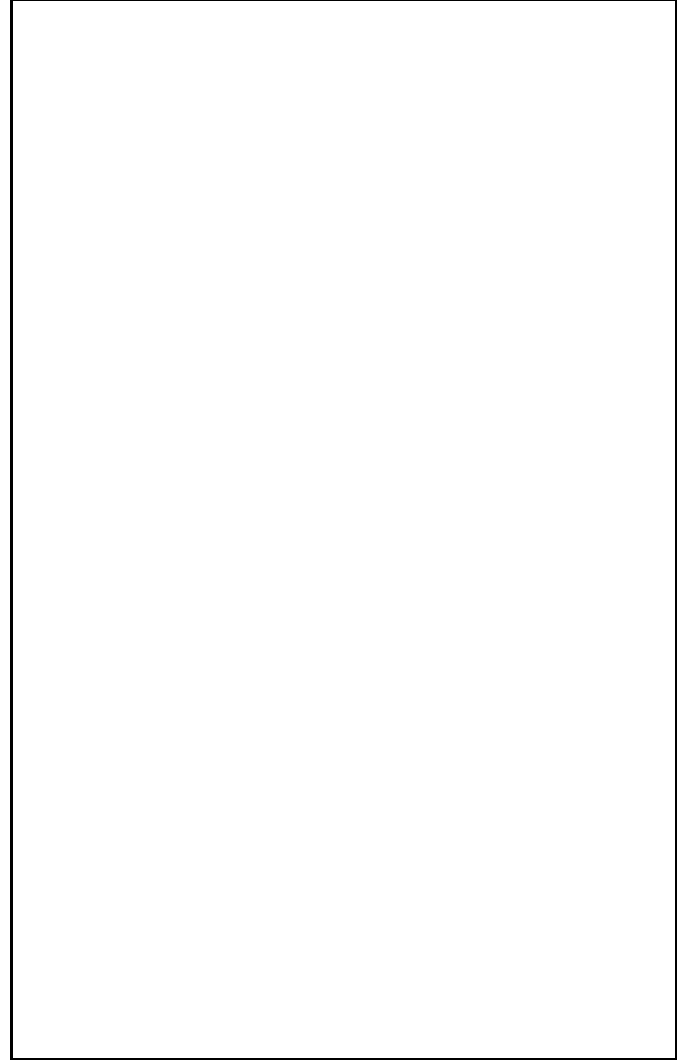


Fig. 5. Cumulative distributions of $L_{\text{FIR}}/L_{\text{B}}$ for barred (filled circles) and unbarred (open circles) galaxies in IF sample. The distributions of early- and late-type galaxies are shown in (a) and (b), respectively.

that barred galaxies are systematically fainter in their FIR emission than unbarred galaxies, which is just the opposite to what Hawarden et al (1986b) and we obtained.

To investigate the difference between their results and those of Hawarden et al (1986b), Isobe & Feigelson examined their data sets omitting the nondetections and survival analysis method, and found that the type SB galaxies are not very different from the SA galaxies ($P \sim 0.12$). They concluded then that the difference may be due to their use of different samples, but not due to methodological bias.

To make a comparison between Isobe & Feigelson's results and ours, we have adopted their approach to omit survival analysis method and sources with no detections at $12\mu\text{m}$ and $25\mu\text{m}$ from their sample, the SAB type galaxies are also omitted as before. The distributions of log

$L_{\text{FIR}}/L_{\text{B}}$ for the resulting sample (IF sample hereafter) are indicated in Fig 5a and Fig 5b, for early- and late-type galaxies, respectively. It is obvious from Fig 5b that the mean $L_{\text{FIR}}/L_{\text{B}}$ for late-type barred sources ($N_{\text{B}} = 13$) is not different from that of unbarred ($N_{\text{N}} = 15$) galaxies ($0.0867/0.0918$, $p_{\text{t}} \sim 0.85$). While the early-type subsample contains only 18 galaxies (Fig 5a) it immediately appears that, as found by IF, barred galaxies are less luminous than unbarred galaxies, by a factor of about 1.8.

3.4. Summary of comparison

Generally, the mean $L_{\text{FIR}}/L_{\text{B}}$ for the early-type galaxies in the IF sample is about 11. times lower than that of the early-type BG sample ($0.0613/0.702$, $p_{\text{t}} \sim 5.8 \times 10^{-7}$), and 2.3 times lower than that of the early-type HP sample ($0.0613/0.141$, $p_{\text{t}} \sim 0.022$). Statistically speaking, they are all significantly different.

In terms of $L_{\text{FIR}}/L_{\text{B}}$, the above various samples cover over varying intensities of relative star formation rate. Especially, early-type IF sample covers over rather weak region of $L_{\text{FIR}}/L_{\text{B}}$, while BG sources cover over a relative strong region of $L_{\text{FIR}}/L_{\text{B}}$. From the analyses in Sec.3.1, 3.2, and 3.3 we have seen that the bar-enhancement becomes striking over the region of strong $L_{\text{FIR}}/L_{\text{B}}$. And the bar-reduced SFR applies to a region of rather weak $L_{\text{FIR}}/L_{\text{B}}$. Different conclusions come from samples with different $L_{\text{FIR}}/L_{\text{B}}$ coverage.

To illustrate this further, and to explore transition thresholds, we have therefore combined all the samples defined above to give a sample with a much wider range of $L_{\text{FIR}}/L_{\text{B}}$ than any of the component subsamples. Despite being statistically more complicated, its large dynamic range will assist the investigation of transitions between IR property regimes.

Fig 6a shows the $L_{\text{FIR}}/L_{\text{B}}$ distribution of early spirals for the “combined” sample. As expected, it illustrates clearly the dependences on barred morphology in the different IR regimes. For low SFRs, among galaxies with $L_{\text{FIR}}/L_{\text{B}} < 1/10$, this ratio is 1.5 times *lower* among barred than among unbarred galaxies (at significance $p_{\text{t}} \sim 0.07$), consistent with the results by Isobe & Feigelson (1992). Conversely, among high-SFR galaxies with $L_{\text{FIR}}/L_{\text{B}} > 1/3$, the mean value of this ratio is 1.6 times *higher* for barred than for unbarred systems ($p_{\text{t}} \sim 0.007$), which is in agreement with the results of Hawarden et al (1986b), Devereux (1987), Puxley et al. (1988), and Dressel (1988). For the region in between, $1/10 < L_{\text{FIR}}/L_{\text{B}} < 1/3$, the distributions of barred and unbarred systems are similar.

Also as might be expected from Devereux’ results (1987), the late type systems from the combined sample, Fig 6b, show no significant differences between barred and unbarred systems ($p_{\text{t}} \sim 0.65$).

Fig 7a illustrates the distribution of the S_{25}/S_{12} color for the entire “combined” sample. Barred and unbarred

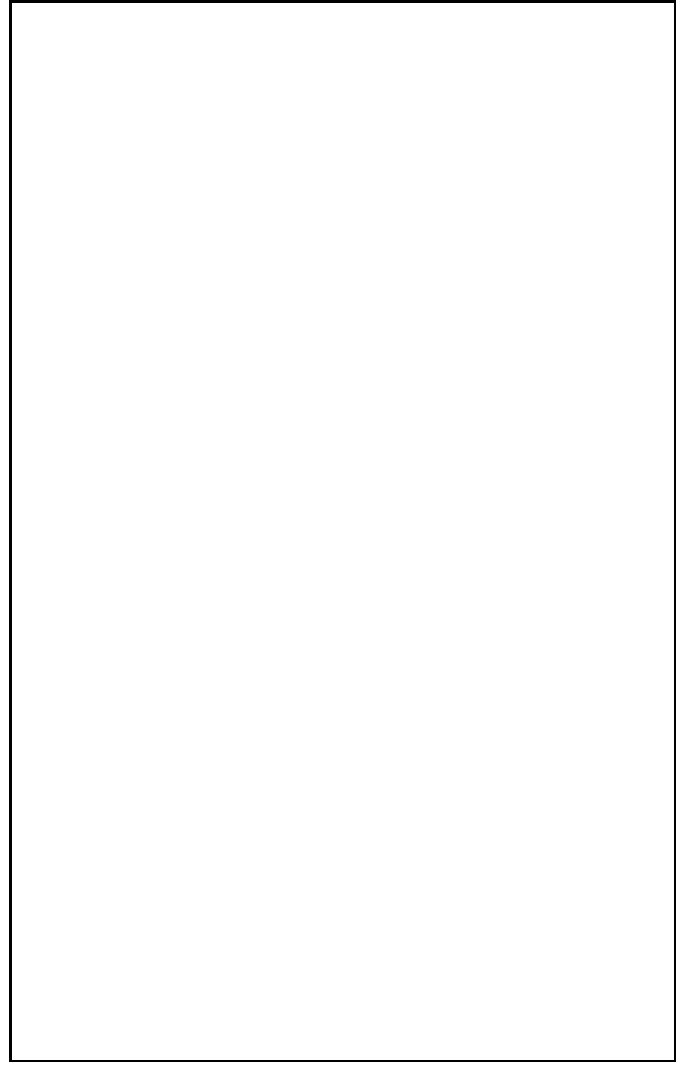


Fig. 6. Cumulative distributions of $L_{\text{FIR}}/L_{\text{B}}$ for barred (filled circles) and unbarred (open circles) galaxies in the “combined” sample. The distributions of early- and late-type galaxies are shown in (a) and (b), respectively.

distributions are obviously very dissimilar ($P \sim 0.011$ from KS test), the barred systems having a markedly wider distribution which is clearly centered at high values of the color ratio: the mean for barred galaxies (1.994) is very significantly higher than for unbarred (1.564), with $p_{\text{t}} \sim 0.003$.

On the other hand, Fig 7b shows S_{25}/S_{12} distribution of the sources for the “combined” sample with $L_{\text{FIR}}/L_{\text{B}} < 1/3$. Once again the distributions of barred and unbarred galaxies are nearly the same. Statistically, both the KS test and the t-test confirm this ($P \sim 0.34$, $p_{\text{t}} \sim 0.31$). These statistical results strongly suggest that the effect of bars on SFR becomes prominent for a sample with $L_{\text{FIR}}/L_{\text{B}} > 1/3$.

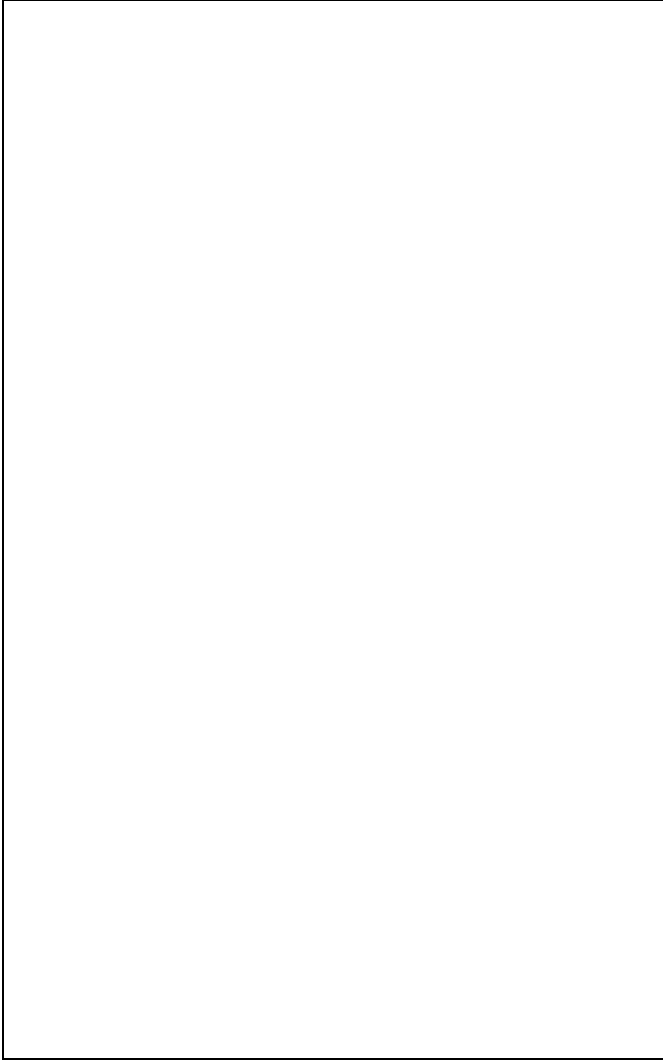


Fig. 7. Cumulative distributions of the $25\mu\text{m}$ to $12\mu\text{m}$ fluxes ratio for barred (filled circles) and unbarred (open circles) galaxies in the "combined" sample. (a) for whole "combined" sample, (b) for galaxies with $L_{\text{FIR}}/L_{\text{B}} < 1/3$ in "combined" sample.

3.5. On the results obtained by Pompea & Rieke (1990)

Pompea & Rieke have observed 15 non-Seyfert, non-interacting galaxies in NIR bands (1990), and found that their observations did not support the suggestion by Hawarden et al (1986b) of bars are a ubiquitous feature of galaxies with $25\mu\text{m}$ excess. In fact, the 15 sources observed by Pompea & Rieke (1990) are IR active, their $L_{\text{FIR}}/L_{\text{B}}$ are all larger than $1/3$, see Table 3, 11 of them are in IRBGS described in Sec 2. . Three of the remaining 4 galaxies, NGC 2146, NGC 5665, and NGC 6574, have flux densities at $60\mu\text{m}$ being larger than 5.4 Jy , the basic selection criterion of IRBGS. The last one, NGC 2784, has been assigned as lenticular galaxies in RC3. Basically, the Pompea & Rieke's sources should belong to IRBGS.

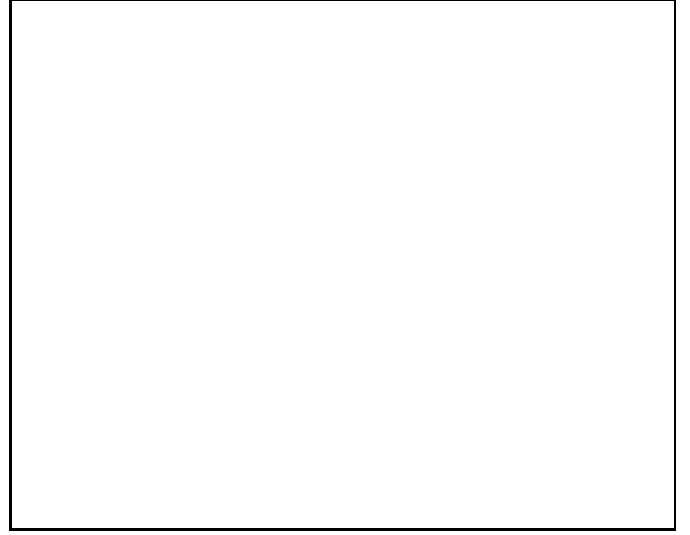


Fig. 8. Cumulative distributions of the $25\mu\text{m}$ to $12\mu\text{m}$ fluxes ratio for galaxies in IRBGS sample. The distributions for types SA, SAB, and SB are indicated by open circles, crosses, and filled circles, respectively. It is obvious that the distribution for the SAB systems is just the same as SA systems.

The suggestion by Hawarden et al (1986b) mentioned above is mainly based on the fact that galaxies with IRAS flux ratio $S_{25}/S_{12} > 2.2$ are exclusively barred (with two exceptions) as shown in their Fig 1. The number ratio of unbarred to barred galaxies with $S_{25}/S_{12} > 2.2$ is $2/23$, about $1/11$. And they speculated that these two sources may in fact be barred. *This is, however, not the case for IRBGS*, as shown in Fig 8. The number ratio of unbarred to barred sources with $S_{25}/S_{12} > 2.2$ is $12/26$, about $1/2$, suggesting that unbarred sources of $S_{25}/S_{12} > 2.2$ are not rare in IRBGS.

According to Pompea & Rieke (1990), 10 of their 15 sources have flux ratio $S_{25}/S_{12} > 2.2$, but only 3 of these galaxies (NGC 3504, NGC 4536, and NGC 5713) are barred, (not the Type listed in Table 3 which are from RC3). We have noticed, however, among the remaining 7 unbarred sources, one galaxies (NGC 2146) is a peculiar galaxies as we pointed out above, other two galaxies (NGC 253, and NGC 2782) are AGN listed in Catalogue by Véron-Cetty & Véron (1993). After removing these three galaxies, the observed number ratio of unbarred to barred sources with $S_{25}/S_{12} > 2.2$ is $4/3$.

Considering the small size of Pompea & Rieke's sample of 15, especially the total number of 10 sources with $S_{25}/S_{12} > 2.2$ as compared to the number of 12 unbarred galaxies with $S_{25}/S_{12} > 2.2$ in IRBGS, we might not be able to say something about the difference between the observed and statistical number of ratio of unbarred and barred galaxies ($4/3$ to $1/2$). But the problem here is certainly not so severe as originally thought.

Table 3. Basic data of Pompea & Rieke (1990) sample

Name	Type	$S_{60\mu m}$	$\log [L_{FIR}/L_B]$	EX \ddagger
NGC 253	.SXS5..	980.080	-0.222	yes
NGC 922	.SBS6P.	5.907	-0.309	
NGC 2782	.SXT1P.	9.632	-0.245	yes
NGC 2990	.S..5*.	5.504	-0.153	
NGC 3310	.SXR4P.	35.972	-0.115	yes
NGC 3504	RSXS2..	22.816	-0.064	yes
NGC 4433	.SXS2..	14.207	0.202	yes
NGC 4536	.SXT4..	32.853	-0.291	yes
NGC 5653	PSAT3..	11.193	0.143	
NGC 5713	.SXT4P.	23.247	-0.058	yes
NGC 5861 \dagger	.SXT5..	11.896	-0.336	
NGC 5936	.SBT3..	9.270	0.137	yes
NGC 2146	.SBS2P.	153.624	0.370	yes
NGC 5665	.SXT5P\$	6.552	-0.216	
NGC 6574	.SXT4*.	14.800	-0.089	
NGC 2764	.L...*.	3.980	-0.041	yes

\ddagger referred to S_{25}/S_{12} excess.

\dagger not observed by Pompea & Rieke.

4. Discussion

4.1. Gas content among Samples

The gaseous ISM is the raw material from which young stars form, and it is reasonable to expect that its availability will affect the vigour of that process. Conversely, therefore, we may expect that samples of galaxies with different SFRs will exhibit correlated differences in gas content. We here explore these possibilities among the early-type galaxies where the effects of barred morphology are most apparent.

Although star formation occurs in molecular, rather than atomic gas, and the resulting IR emission is mostly from dust associated with the molecular material, the current data sets on molecular gas in early-type spirals are still too small to provide good coverage of our sample lists and we must await additional observations. However, plenty of HI data are conveniently available ,e.g. from RC3. We now employ these data in a similar manner to some other groups (see, e.g. Eskridge & Pogge 1991, and references therein).

Fig 9 demonstrates a clear correlation between FIR emission and HI content in the early-type galaxies of all samples, with correlation coefficient $R = 0.66$ for the BG sample, and $R=0.60$ for the HP sample (including the early-type galaxies from the IF sample, because there are insufficient HI data to perform a meaningful analyses for the IF sample alone), showing in Fig 9a and 9b respectively. What the statistical correlation in Fig 9 indicated is the following: galaxies with large FIR emission also tend to have large HI component, or *vice versa*. No trace of association with barredness is apparent.

Fig. 9. Correlation of FIR luminosity with HI content for early-type barred (filled circles) and unbarred (open circles) galaxies. The distributions of galaxies in BG sample, and HP sample are shown in (a), and (b), respectively.

However a much more suggestive result emerges if we subdivide the "combined" sample, as before, at the value of relative IR luminosity where we have found that the IR properties begin to depend on barred morphology, $L_{FIR}/L_B \sim 1/3$, and examine the distributions of HI content. The results are shown in Fig 10. Once again the relatively IR-brighter systems show the morphological dependence, see Fig 10a, while the IR-faint objects do not, see Fig 10b. The barred galaxies above $L_{FIR}/L_B > 1/3$ have mean HI content 1.9 times higher than that of the unbarred objects, a significant discrepancy at $p_t \sim 0.07$. We have shown in Sec 3.4 that for galaxies with $L_{FIR}/L_B > 1/3$ in " combined" sample, the bars strongly enhance the star formation rate, while not for sources with $L_{FIR}/L_B < 1/3$ (not including early-type IF sample). Thus it follows that for galaxies of $L_{FIR}/L_B > 1/3$, the

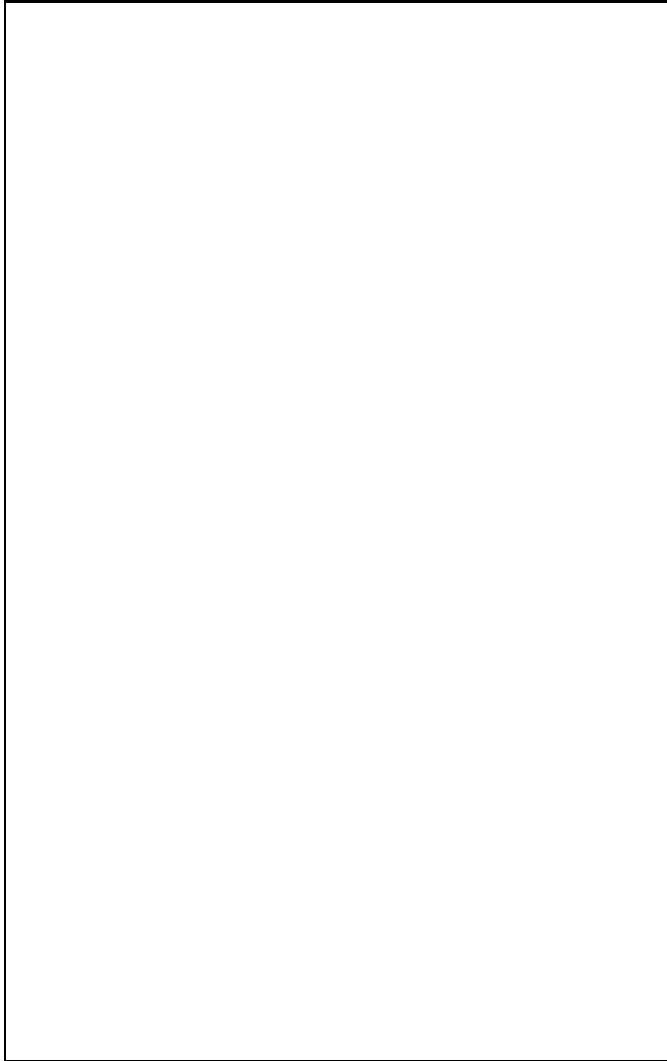


Fig. 10. Cumulative distributions of HI contents for early-type barred (filled circles) and unbarred (open circles) galaxies in the "combined" sample. (a) for galaxies with $L_{\text{FIR}}/L_{\text{B}} > 1/3$; (b) for galaxies with $L_{\text{FIR}}/L_{\text{B}} < 1/3$.

bar-enhanced SFR is associated with the bar-related HI content excess, which we consider, in circumstances, to be highly suggestive of a common mechanism. The results of this investigation will be discussed elsewhere (Gu et al 1996).

We have no intension of directly connecting the HI content with the effect of bars on star formation, shown in Fig 10a, but we would emphasize that the physical nature of enhancements in SFR remains much less clear (see, e.g. Keel 1993). Several recent studies of disk galaxies indicate that substantial amount of FIR flux come from regions which are spatially distinct from either resolved regions of massive star formation or strong CO sources (Jackson et al 1991; Smith et al 1991). One of the possibilities is that the bulk of the FIR comes from something akin to Galactic cirrus. To further clarify the effect of bar on SFR would

need more HI and CO data, especially those observations with spatial distribution, which are under planning.

4.2. Morphological classification

The uncertainties in morphological classification of galaxies will definitely affect our analyses. The way of dividing a sample into early- and late-type systems would partly reduce this kind of influence. In the above separation, we have just followed Combes & Elmegreen (1993) and Devereux et al (1987) to take all galaxies before Sbc type as early-type spirals. And we have found that the statistical difference obtained in Sec. 3 between early-type barred and unbarred galaxies would disappear, like those results obtained for late-type systems, if we put galaxies of Sc type into early-type spirals, indicating that the dividing line between early- and late-type spirals set by Combes & Elmegreen (1993) is basically reasonable.

There is another uncertainty in morphological classification in RC3, i.e. a number of sources have been assigned to S type rather than SA or SB type. In our analyses in Sec 3 or 4, they have been taken as SA type galaxies. If we put all of them into SB types instead, the statistical difference between early-type barred and unbarred systems will be strengthened, and the conclusions drawn for late-type galaxies remain as they were statistically. It follows that the uncertainties of not assigning definite Hubble type may not introduce significant modification to our results.

5. Conclusions

Our analyses have led us to the following conclusions:

1. Stellar bars in spiral galaxies do indeed affect star formation rates, but only in types S0/a - Sbc, not in later classes.
2. The influence of bars on star formation rate is perceptible only in galaxy samples which locate at the relatively high end of the $L_{\text{FIR}}/L_{\text{B}}$ range, probably because most galaxies so affected have thereby been moved into those samples. The enhancement effects of barred morphology on SFRs become apparent for $L_{\text{FIR}}/L_{\text{B}} > 1/3$, but can be discerned in less IR-luminous systems in the mid-IR color introduced by Hawarden et al. (1986a), which is a more sensitive indicator of the SFR than a simple comparison of luminosities or of FIR excesses. Our analyses indicate that sources with $L_{\text{FIR}}/L_{\text{B}} > 1/3$ play an important role in the statistics of IRAS color (S_{25}/S_{12}) approach.
3. At the other end of the $L_{\text{FIR}}/L_{\text{B}}$ range bars act to reduce the IR luminosity of a galaxy, though probably not its SFR.
4. There is therefore a huge and highly significant difference between the effects of barredness in the most IR-luminous sample (the BG sample) and the least IR-luminous (the IF sample) in our study. Most of the

different conclusions about the influence of this morphology on SFRs arises from studies of samples falling at different locations within the $L_{\text{FIR}}/L_{\text{B}}$ range.

5. The fact that distributions of HI content behave similarly to those of IR properties suggests that the availability of fuel is a governing factor in the effects of bars on star formation rates.

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